Distressed in the queue? Psychophysiological and behavioral evidence for two alternative car-following techniques

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Abstract

Background. Nature offers numerous examples of animal species exhibiting harmonious collective movement. Unfortunately, the motorized *Homo sapiens sapiens* is not included and pays a price for it. Too often, drivers who simply follow other drivers are caught in the worst road threat after a crash: congestions. In the past, the solution to this problem has gone hand in hand with infrastructure investment. However, approaches such as the Nagoya Paradigm propose now to see congestion as the consequence of multiple interacting particles whose disturbances are transmitted in a waveform. This view clashes with a longlasting assumption ordering traffic flows, the *rational driver* postulate (i.e., drivers' alleged propensity to maintain a safe distance). Rather than a mere coincidence, the worldwide adoption of the safety-distance tenet and the worldwide presence of congestion emerge now as cause and effect. Nevertheless, nothing in the drivers' endowment impedes the adoption of other car-following (CF) strategies. The present study questions the *a priori* of safety-distance, comparing two elementary CF strategies, Driving to keep Distance (DD), that still prevails worldwide, and Driving to keep Inertia (DI), a complementary CF technique that offsets traffic waves disturbances, ensuring uninterrupted traffic flows. By asking drivers to drive DD and DI, we aim to characterize both CF strategies, comparing their effects on the individual driver (how he drives, how he feels, what he pays attention to) and also on the road space occupied by a platoon of DD robot-followers. **Methods**. Thirty drivers (50% women) were invited to adopt DD/DI in a driving simulator following a swinging leader. The design was a repeated measures model controlling for order. The CF technique, DD or DI, was the within-subject factor. Order (DD-DI / DI-DD) was the between-subjects factor. There were four blocks of dependent measures: individual driving performance (accelerations, decelerations, crashes, distance to lead vehicle, speed and fuel consumption), emotional dimensions (measures of skin conductance and self-reports of affective states concerning valence, arousal, and dominance), and visual behavior (fixations count and average duration, dwell times, and revisits) concerning three regions of the driving scene (the Top Rear Car –TRC- or the Bottom Rear Car –BRC- of the leading vehicle and the surrounding White Space Area -WSA). The final block concerned the road space occupied by a platoon of 8 virtual DD followers. **Results**. Drivers easily understood and applied DD/DI as required, switching back and forth between the two. Average speeds for DD/DI were similar, but DD drivers exhibited a greater number of accelerations, decelerations, speed variability, and crashes. Conversely, DI required greater CF distance, that was dynamically adjusted, and spent less fuel. Valence was similar, but DI drivers felt less aroused and more dominant. When driving DD visual scan was centered on the leader's BRC, whereas DI elicited more attention to WSA (i.e., adopting wider vision angles). In spite of DI requiring more CF distance, the resulting road space occupied between the leader and the 8th DD robot was greater when driving DD.

Keywords

Car-following; Driving behavior; Psychophysiological correlates; Traffic congestion; Waves

1. Introduction

Thousands of starlings (*Sturnus vulgaris*) perform swift changes of speed and position in coordinated and mesmerizing formations in the air to evade predators (Goodenough et al., 2017). Dozens of caterpillars (*Thaumetopoea pityocampa*) follow each other in perfect harmony to find their place in the forest and could keep such mate-following harmony for as long as half a day before disaggregating (Fitzgerald, 2003). However, every bunch of motorized human (*Homo sapiens sapiens*) in the world takes pains to follow each other without being trapped in the so-called *phantom traffic jams* (Gazis and Herman, 1992) or traffic congestions pervasively emerging in traffic for no apparent reason. We may conclude there is certain wisdom of nature drivers' keep somehow neglecting. With more than one billion drivers in the world by 2020 (a conservative estimation, see Sperling and Gordon, 2009), the expected two thirds of the world's population living in cities by 2050 (UN, 2018), and traffic pollution already causing more deaths than crashes (Caiazzo et al., 2013) this neglect is increasingly untenable.

Our disregarding of lessons from nature hides another important neglect: the wave properties of dense traffic. Envisioning traffic flows as "a dynamical phenomenon of a many-particle system" (Sugiyama et al., 2008; p. 2) is surprisingly recent. A central element of this new perspective is a changing focus from pairs of cars (the leader, the follower) to broader systemic interactions (e.g. the endogenous dynamics of cars that platoon). Back in 2008, researchers in the so-called Nagoya experiment created an artificial jam. Drivers followed each other in a circle of 230 m perimeter under the premise: *follow the vehicle ahead in safety in addition to trying to maintain cruising velocity*. Participants drove and kept a free flow. But, when the number of drivers rose to 22, fluctuations tripping backward broke the free flow and several vehicles stopped for a moment to avert crashing. At a given point, even a single car's braking was transmitted backward through a column of cars, forming the typical shockwave (soliton) that eventually brought some cars to a complete halt (see also Tadaki et al., 2013; Stern et al., 2018).

A third neglect keeps human drivers away from the Golden league played by starlings or caterpillars. The majority of car-following engineering models (Saifuzzaman and Zheng, 2014; Sharma et al., 2019) assume that the systematic adoption of safety distance on the part of drivers is a natural or dispositional trend (Pariota, Bifulco, and Brackstone, 2016; Wilson, 2008). Consider the *rational driver* postulate (Bando et al., 1995; Wilson, 2008), e.g., "drivers typically increase their acceleration when there is an increase in the spacing…and reduce it in the opposite situation. The same happens with respect to relative speed." (Pariota et al., 2016; p. 1033). Millions of observations worldwide confirm this behavior: the systematic approach of the follower to the leader (coupling). However, no psychological theory presumes a genetic or biological endowment ready for the massively observed CF behavior. Some other living organisms (ants, bees, caterpillars, and the like) exhibit complex behaviors derived from such endowments, but not humans. Drivers were taught or learned somehow to keep the safety distance. Going back to the physical-mathematical foundations backing the Nagoya paradigm, two main options emerge when following a stopping-and-going car: summing (imitating) and offsetting (counterbalancing) that disturbance (Blanch et al., 2018). We now illustrate how these options may shape traffic flows quite differently.

1.1. Sketching two car-following approaches: Traffic flow theory vs WaveDriving

Two main approaches model the basic form of the car-following process (i.e., one vehicle follows a leader in the same lane). The first approach is broadly known as classic *Traffic Flow Theory* (TFT; Ni, 2016; Treiber and Kesting, 2013). The radical starting point of this approach is that of an observer who takes a snapshot of the car-following situation and states that the road space occupied by a vehicle depends on 1) The length of the car, 2) The separation between the vehicles (Fig. 1, A). The formalization of that approach can be traced back to the period 1958-1963 when the core stimulus-response CF models and theories by Chandler et al., (1958), Kometani and Sasaki (1958), Helly (1959), or Michaels (1963) were developed. Such core models stressed which stimulus (relative velocity, safety distance, desired speed, distance or acceleration, or visual angles subtended by a lead vehicle) guides the follower response (normally, acceleration). A complex family of CF models has evolved from that departure point to our days (Brackstone and McDonald, 1999; Saiffuzaman and Zheng, 2014).

We will name the second approach *WaveDriving* (WD; see Blanch et al., 2018). Here, the observer prefers taking a motion picture of the situation and states that the road space occupied by a vehicle depends on 1) The length of the car, 2) Safety distance, 3) The anti-jam zone, 4) The unused or remaining space (Fig. 1, B).

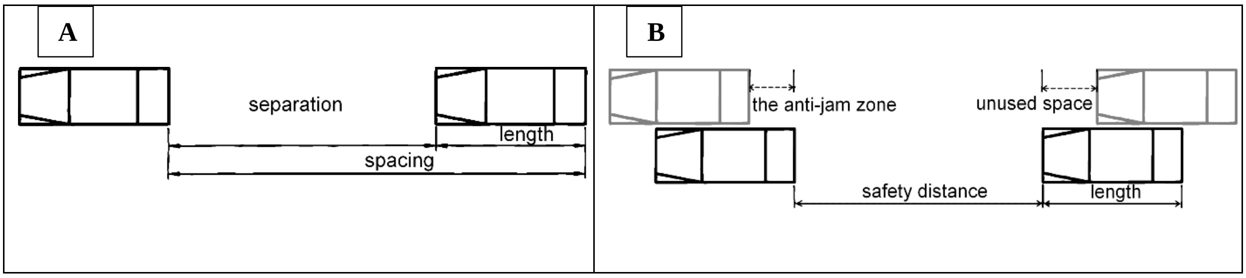

Figure 1. Traffic Flow Theory (A) versus WaveDriving (B)

Assuming TFT, the observer notes that the two vehicles (leader and follower) keep a speed *v* and a separation between them. However, the separation is actually deduced from a series of assumptions (constant speed of the platoon and average space being kept). We may apply this scheme sequentially and create a platoon of vehicles, obtaining the fundamental equation for this type of engineering:

$$q = \bar{v}_e k \qquad (1)$$

that may be phrased as “The flow of vehicles in a lane q is the product of the average spatial velocity $\bar{v}_e$ by the average density k.”. It is important to note that this is a statistical equation; it refers to average values, which can be applied to everything that goes through a section: fluids, gases, conveyor belts or road traffic. If we perform a macroscopic statistical study we would get the fundamental diagram of traffic flow (Smeed, 1968) a graph parabola (Fig. 2, A), with two areas well apart: 1) a zone above the maximum intensity (attained at point M), represented by the continuous line, that is adjustable by least squares (the area of self-paced free flow, or fluid traffic), and 2) a lower zone, beginning at point B and shown by the discontinuous line, reflecting a place of uncertainty (not adjustable mathematically). This is the area of traffic jams and forced-paced traffic, larger than the area of stable traffic. However, B and M are coincident, why can't vehicles circulate below a certain "critical" speed fluidly?

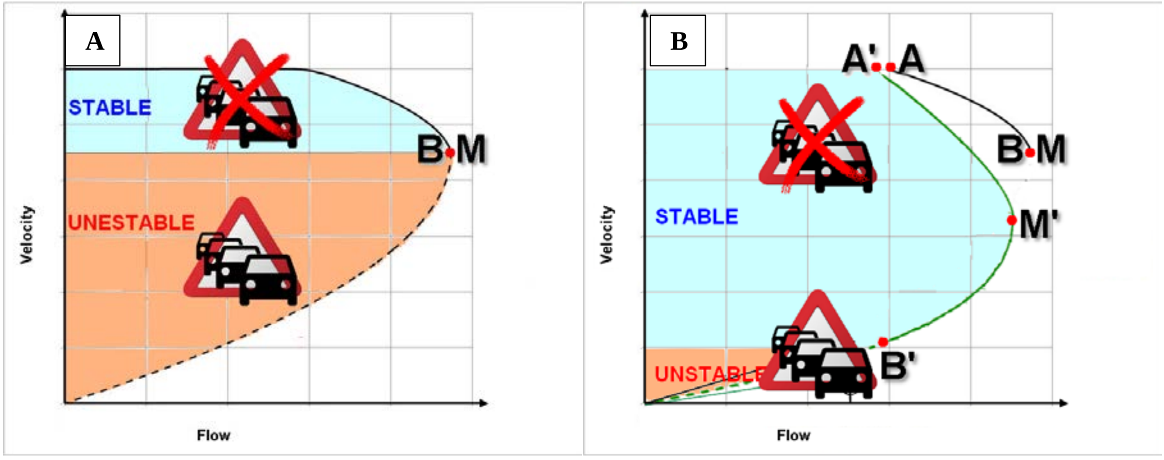

Figure 2. Graphical representations of the flow stability areas predicted by TFT (A) and WD (B)

The answer is provided by the WaveDriving approach because the observer (as researchers at Nagoya did) pays attention to variations through the whole process. Correspondingly, the separation between cars (Fig.1, A) is decomposed into three variables in Fig. 1, B. The black curve in Fig. 2, B shows the typical relationship between velocity and flow under DD. Point A is maximum flow at the speed limit (e.g., 120 km/h). Ideally, maximum flow at the corresponding speed (e.g., 70-90 km/h) should be kept, but, given the oscillatory nature of traffic flows (reaction time, summing waves), this state cannot last long; a jam occurs and speed and flow decrease. The green curve in Fig. 2.B represents DI. A' is maximum flow at the speed limit. Forced traffic begins at B'. Maximum flow is attained at M'. B' and M' are not coincident so M' is not as precarious as M and can last much longer. In sum, we propose a kind of gambit: gently sacrifice maximum intensity to gain flow stability. This scenario is pictured in Fig. 1, B. The speed of the first vehicle varies, but the second one, for convenience in our explanation, keeps a constant speed of equal value as the average speed of the first vehicle. Let us list the variables concerning the follower's vehicle: 1) Its velocity (approximately constant), 2) The safety distance, 3) A variable space, that defines the anti-jam zone, necessary to be able to keep a constant speed, 4) The unused space (because even if the follower keeps the same average speed of the swinging leader, he can do it further away or closer). According to the WD approach, if we apply this scheme sequentially, we create a platoon of vehicles and get the fundamental equation of traffic for this type of engineering:

$$W_n = W_1 + \Sigma\ {}_d W_i \qquad (2)$$

that may be phrased as "The motion wave of the last vehicle W_n is the wave of the movement of the first vehicle W_1 plus the management of the space made by each of the following drivers $\Sigma_d W_i$.". Note that it is not a fundamental statistical equation, but an exact one, without loss of variables when taking average values. Waves appear in the equation because it refers to periodic movements or oscillations. So the best mathematical demonstration of WaveDriving is not reached through a cinematic approach (as most TFT models do), but through wave mathematics (although a closer examination of such fundamentals is out of the scope of this paper). Now, if we analyze the intensity-velocity graph (Fig. 2, B), we see clear differences: 1) The stable traffic zone is greater than the forced traffic zone, 2) However, a price is paid for it: *instantaneous capacity* decreases, 3) The maximum intensity speed no longer determines the boundary between the two zones, 4) The velocity of fluid traffic remains below that of maximum intensity. In sum, adopting TFT we bring flows to a higher, but precarious, speed and density; at some point, the equilibrium breaks and jams emerge. Adopting WaveDriving, optimal velocity is lower, but flows keep uninterrupted for much longer.

What's the right approach? Both approaches are closely related. If the WD approach is taken, with its four variables (1. speed; 2. safety distance; 3. anti-jam zone; 4. unused space) and we make the third and fourth variables worth zero, the result is the classical Traffic Flow Theory. In other words, the third and fourth variables define the level of stability of the platoon and the correct use of space. This is why drivers who only drive with safety distance and speed produce traffic jams: as soon as the speed of the leader is not constant, and oscillates, the disturbance trips backward through the whole platoon till one of them stops (the ‘keep-safety-distance’ principle turns platoons of followers into perfect means for wave transmission). According to the TFT approach, a traffic jam occurs because the road reached its capacity; more lanes are needed (HCM, 2016). According to the WaveDriving approach, that traffic jam occurs because *drivers reached their limits to manage available road space*. Although current developments of Traffic Flow Theory (e.g., Ni, 2016) include waves in their formalizations, such models keep seeing drivers as *rational ones*, i.e., always and uniquely aiming to keep the safety distance. The result is that we benefit from additional modeling to describe the complexities of traffic flows (wave mathematics), but we keep far from the solution to change them substantially.

1.2. Drivers’ radical oscillation: possibilities

Envisioning traffic flows as potential means for wave transmission is coherent with human driving patterns. Drivers move amidst a perennial oscillation either following a swinging leader, a stable leader or when driving with no traffic at all. This was implicit in early CF theories under the Action Point (AP) paradigm (Brackstone, Sultan and McDonald, 2002; Pariota and Bifulco, 2015) and pictured by the characteristic close-following spirals in different studies (Pariota et al., 2016; Wagner, 2011). Other CF models describe instability typical of transition phases between free-flow and congestion (Orosz, Wilson and Krauskopf, 2004), especially when the leader's speed varies (Pariota et al., 2016). Driving involves a regulation process (concerning speed, acceleration) in the form of a tracking-loop (Adams, 1971). Driving behavior is described by most models as a hierarchical task comprising three performance levels, top-down: navigation (e.g., route selection), maneuvering (e.g., reaction to traffic, speed choice, control of longitudinal guidance) and control (use of gas/brake pedals to achieve the previous level's target action) (Horst, 2013). With no adverse external factors (e.g., heavy traffic, curves, fog), drivers' speed systematically oscillates around a mean value due to the regulation process (control). This oscillation, consubstantial to driving, expresses itself when driving alone, when car following at constant speed, for high or low speed, and high or low visibility. Data shows that stable oscillatory patterns at 1 m/s around the mean speed are adopted (Wille, 2011; Wille and Debus, 2005).

The oscillatory pattern reported by different studies comes per se, is systematic, and is near-constant in different driving contexts, the CF context only makes it more acute (Sugiyama et al., 2008; Tadaki et al., 2013). Drivers following an oscillatory leader have two main options themselves: just being reactive (imitate) or anticipate, becoming proactive. Most drivers in the world have been taught to be reactive, *Driving to keep Distance* (DD), which in turn sums and enlarges disturbances throughout the CF platoon. The alternative to cope with a lead oscillatory vehicle (the shockwave origin), is anticipating the stop-and-go pattern and becoming shockwave proof offsetting or damping waves and keeping a uniform speed: *Driving to keep Inertia* (DI). This paper compares the effects of these two CF techniques upon basic performance parameters (e.g., speed, distance to the leader, fuel consumption). Proposing these orthogonal CF techniques (aim for uniform distance vs. uniform speed) points to an alternative to reshape traffic flows, opposes the Normative Driving Behavior concept as a unique or dispositional driving mode and states that drivers can also be proactive, changing operative mode from automatic to controlled (Charlton and Starkey, 2011) and applying DD or DI as appropriate (Blanch et al., 2018).

1.3. Car-followers: the emotional platoon adapting to flow variations

Proposing an alternative CF technique raises an important question: how do drivers' adaptation to CF disturbances, either adopting DD or DI, impact upon their cognitive, emotional and perceptual resources. Although experts rightly state that "Most driving is spent constrained by a vehicle in front" (Evans, 1991; p. 114), motorized human beings move together for little more than a century now. Drivers are not endowed with specific cognitive-emotional programs to follow other drivers in a functional way: inadequate distance and speed between vehicles boost cognitive load (Lewis-Evans, de Waard and Brookhuis, 2011), foster adverse affective and emotional states, anger provoked by other drivers in particular (Mesken et al., 2007; Zhang and Chan, 2014), aggressive behavior (Shinar and Compton, 2004) and crashes (Davis and Swenson, 2006). The fundamental driving goal is arriving within the expected time to the destination. Facing unexpected dense or congested traffic threatens driving goals, frustrating many drivers, and encouraging aggressive driving.

Classical approaches on the elicitation of discrete emotions (Lazarus, 1991) point to a dual process: the primary appraisal process tells drivers the event (e.g., congestion) is actually relevant for their goals (e.g., negative, blocking progress), and the secondary appraisal process brings drivers to evaluate the possibilities to cope with the situation and its consequences: drivers feeling some control and blaming other drivers, will feel anger. Angry drivers feel more in control, doing more optimistic risk appraisals, likely driving faster, above the speed limit (Mesken et al., 2007), showing more prominent speed variations (Deffenbacher et al., 2003), and crossing more traffic lights in yellow (Abdu, Shinar and Meiran, 2012). Angry drivers may come too close to the leading car to the point of tailgating, as a maneuver to indicate “move, I’m in a hurry” (Song and Wang, 2010). However, reducing heading distances turns the vicious circle on tightening CF space, encouraging platoon instability and facilitating disturbances tripping backward, worsening congestion (Ni et al., 2017). Having said this, eliciting discrete emotions (e.g., fear, anger) in a CF laboratory setting entails difficulties that are beyond the scope of our study. Instead, we are adopting a general approach based on elementary emotional dimensions such as arousal, valence and dominance (Lang, Bradley and Cuthberg, 1999; Frijda, 2001), the basis upon which discrete emotions are built (e.g., high arousal and low valence compound emotions as anger and anxiety; Cai and Lin, 2011; Zhang and Chan, 2014). WaveDriving is a CF strategy in the process of exploration, just as its effects on emotions are too (but see Lucas-Alba et al, 2017). DD is a reactive technique while DI is proactive, requiring more anticipation. This could result in a higher mental workload, although DI also allows for more control of the CF situation (the driver, not the leader, determines speed regulation). This study aims to characterize the effects of DD/DI upon basic emotional dimensions such as valence, arousal, and dominance.

If emotions are the energy behind the wheel, direction relies on perception. Driving (CF in particular) is a preeminently visual task (Lee, Lee, and Boyle, 2007), demanding focused attention on the traffic ahead. Early in the 1960s, the AP model proposed a specific psychophysiological mechanism to explain CF discontinuities in the acceleration and deceleration phases: a lead vehicle’s visual extent (size) is the specific stimulus for drivers during CF (Pariota and Bifulco, 2015). Besides this elementary psychophysical component, a consequence of speed variations during the CF process, visual patterns shown by expert vs novel drivers matter. The former anticipates, looking ahead and keeping wider vision angles, while the latter normally focus their visual resources on the nearest section and stimulus on the road (Huestegge, 2010). When following a swinging leader in dense traffic, DD demands little more than a swift reaction (accelerate), imitating the leader, being ready to stop, all demanding a narrow and somehow stereotyped perceptual focus, keeping smaller vision angles, typical of novel drivers. Conversely, DI demands anticipation and constant evaluation to calculate the right (and varying) distance needed to keep a uniform speed, looking well ahead and adopting wider visual angles, all features shared with expert drivers. Consequently, although never examined to date, we expect that driving DI will yield visual patterns akin to expert (e.g., wider visual span, shorter fixations) while driving DD will yield visual patterns more typical of novel drivers (narrower span, longer fixations).

1.4. Goals of the study

The study aims to characterize two elementary CF techniques termed DD (Driving to keep Distance) and DI (Driving to keep Inertia) in some relevant dimensions. Previous studies confirmed that drivers can adopt either DD or DI to follow a swinging leader and that these techniques show opposite patterns of speed and distance variability (Blanch et al., 2018). However, this is an important finding worth replicating, because this unexplored (and neglected) ability is the key to uninterrupted traffic flows. Additional pieces of evidence concerning perceptual and affective factors are also sought. DD drivers just react to someone else behavior, don’t have much control or autonomy: low valence, high arousal, and low dominance could be expected. DI drivers face a more complex regulation; on the one hand, having to take more variables into account could bring on cognitive overload (hence, low valence, high arousal). On the other hand, they may feel more autonomous, competent and dominant driving DI: high valence, low arousal, and high dominance could compensate for cognitive complexity. Our study aims to explore these possible outcomes in the emotional domain. Finally, the reactive/proactive dichotomy accompanying DD/DI alternatives may influence visual behavior too. Drawing on studies comparing expert and novel drivers, we propose that DI elicits an expert visual search pattern from participants, while DD elicits a non-expert visual search pattern from participants. Conversely, we expect that DD drivers focus on the blinkers/brakes zone of the car ahead while DI drivers explore other areas as well. Our last question regards how these CF techniques differ in terms of the overall road space taken by a platoon of 8 bot-followers. According to the WaveDriving approach, DI requires and additional anti-jam distance to keep inertia, but adopting a uniform speed promotes platoon stability behind. Is the distance between the participant and the 8th bot-follower finally greater for DD or DI? Our expectation is positive (Blanch et al., 2018 –study 3), but the possibility of lost space considering the whole platoon needs additional probes.

2. Methodology

2.1. Goals

The study aimed to check if A) the same driver could drive in DD and DI modes when following a lead ‘swinging’ car; B) drivers could follow the driving techniques by heeding a 10 s instruction (three sentences); C) drivers keep the driving instruction as requested (e.g., not turning to DD instead), D) participants driving DD vs. DI differ in terms of emotional terms (arousal in particular), E) participants driving DD vs DI differ in visual patterns (narrow focus vs wider exploration of space ahead); E) the space occupied by eight virtual DD drivers following either a DD or a DI participant differed.

2.2. Participants

The sample was composed of 30 people, 15 men and 15 women, falling in a 19-35 year age range (mean age 21.77, SD = 4.17). The basic requirement was to have a driving license. The sample presented a medium-high education level (73.3% were university graduates, 23.3% were high school graduates and 3.3% had vocational training). All of them had a driving license (M = 3.26 years; SD = 3.79), from a half a year to fourteen years, and 46.7% of them drove less than 10,000 km a year. They were asked how often they drove by highway/motorway with a scale from 1 (never) to 4 (very often), the average being 3.30.

2.3. Design

The design was a repeated measures model controlling for order. The manipulation of the type of driving technique applied to follow the lead vehicle, either focused on distance (DD) or focused on inertia (DI), was the within-subject factor. Order (DD-DI / DI-DD) was the between-subjects factor. The set of dependent measures formed four blocks: individual driving performance (accelerations, decelerations, crashes, distance to lead vehicle, speed and fuel consumption), emotional dimensions (measures of skin conductance and self-reports of affective states concerning valence, arousal, and dominance), and visual behavior (fixations count and average duration, dwell times, and revisits) concerning three regions of the driving scene: the leader’s Top Rear Car (TRC), Bottom Rear Car (BRC) and the White Space Area (WSA), the wider area surrounding the car (Fig. 3). The last block concerned the road space occupied by a platoon of 8 virtual DD followers with regards to either the participant or the leader vehicles.

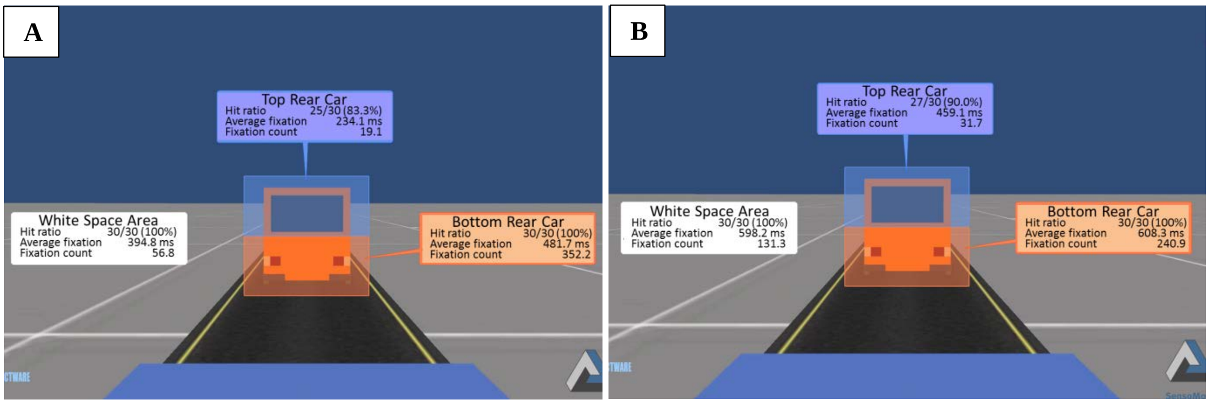

Figure 3: TRC, BRC and WSA for DD (A) and DI (B). Hit ratio indicates how many participants looked at least once into the area of interests (e.g., top rear car in Figure 3.A was seen by 25 out of 30 participants). Average fixation indicates the average duration of each fixation in an area of interest (e.g., 234.1 ms in the previous case). The fixation count indicates the average number of all fixations for selected participants (e.g., the 25 participants averaged 19.1 fixations in the top rear car area in Fig. 3, A).

2.4. Materials

The study was carried out in the Faculty laboratories of a Spanish University. Participants carried out the task in a room equipped with two computers but they could not see the monitor which displayed the participants' psychophysiological performance. Skin conductance (SC) was recorded with a Biopac MP36 (Biopac Systems Inc., Goleta, CA, USA) at a sampling rate of 50 Hz using two disposable Ag-AgCl electrodes attached to the left hypothenar eminence. Mean SC (in microsiemens, µS) was calculated for the three experimental periods (see below). The MP36 unit was connected to a standard PC with a Windows 7 operating system.

Self-report measures of the affective state were collected with the “Self-Assessment Manikin” (SAM) scale (Lang, Bradley and Cuthbert, 1999), a nonverbal pictorial assessment technique concerning three general affective dimensions: valence, arousal, and dominance. The SAM scale has been validated with the Spanish population (Moltó et al., 1999) and was applied to measure the affective state after the task in the simulator. The valence scale goes from 1 (*displeasure*) to 9 (*pleasure*), the arousal scale goes from 1 (*aroused*) to 9 (*relaxed*) and the dominance scale goes from 1 (*dominated*) to 9 (*dominant*).

Eye-movements were recorded using a SensoMotoric Instruments GmbH 500-Hz (binocular; spatial resolution: 0.03°; gaze position accuracy: 0.4°) RED system eye tracker (Teltow, Germany). For saccade and fixation detection parameters, we used a velocity-based algorithm with a 40°/s peak velocity threshold and 80 ms for minimum fixation duration.

An early goal for this project was designing a 3D driving simulator to run remotely on a standard PC. ReactFollower (Impactware, 2014), based on UNITY software, was developed and customized to change parameters (speed, frequency of stop-and-go cycles, etc.) externally, via XML. The focus was on creating simple DD/DI scenarios, with a lead car's adopting different oscillatory patterns. In the present study, participants drove in three scenarios, always in one lane and not being able to exit or overtake: A) driving alone on the road (in a natural position for drivers, behind the wheel); B) driving behind another car traveling at constant speed of 3 m/s (10.8 km/h); C) driving behind another car traveling with stop-and-go cycles of a sinusoidal function built at a mean speed of 3 m/s, ranging from 0 m/s to 6 m/s (data is presented only from C). Participants could control their car's acceleration/deceleration only by pressing up/down arrows on the keyboard. When "up" was pressed, the car accelerated and maintained a constant speed. When "down" was pressed, it decelerated and maintained a constant speed. As with cruise control, a common option in today's driving, each speed change was incremental: to accelerate or decelerate continually meant repeatedly pressing the keys. The simplest option (keyboard) was preferred to enable all subjects to use the software with basic hardware equipment, and to level differences in expertise with video game keyboards. The road had no changes in horizontal or vertical alignment; the impression of speed was created by horizontal lines moving in the White Space Area. The only requirement was altering speed-distance on a straight flat lane. The brake lights came on every time the leading car slowed down. The driving simulator worked on an HP TouchSmart iq522es with a 23-inch screen, NVIDIA GeForce 9300m GS video card and 4 GB RAM, Intel Core 2 Duo Processor T6400 2.00 GHz, and Windows 10 operating system. A precision Apple USB keyboard (PCB DirectIN V2012) was used. The simulator collected, among others, variables for speed, distance to the leader, and fuel usage (a gross estimate obtained considering variations in speed per frame, table 1).

2.5. Procedure

Participants were first monitored, checking the proper evaluation of skin conductance, including a 4 min baseline. Participants then followed scenarios A (a 4 minute drive on the simulator) and B (a 4 minute drive following a leader at constant speed) designed as an adaptation to operate with the simulator. Then the experimental phase proper began. Participants in scenario C were told to follow the lead swinging car and adopt DD or DI; neither option was given an explicit verbal label. The group performing DD first followed this instruction: "In the simulated driving scenario that you will enter, you will see a vehicle ahead of you and it will not move at a constant speed. Sometimes it will go faster or slower. We ask you to travel behind that vehicle as closely as possible without ever risking a crash." Right after this brief instruction (certainly an extreme case, mirroring stop-and-go cycles under forced traffic), they performed on the simulator and once this first task was finished, they were given the SAM scales. Following this, the instruction for DI was provided: "In the simulated driving scenario, you will see a vehicle ahead of you and it will not move at a constant speed. Sometimes it will go faster or slower. We ask you to travel smoothly behind the vehicle and maintain a constant speed, without letting the lead vehicle move too far away.". The SAM scales were filled in again. For the group performing DI first, the instructions' order was reversed.

3. Analysis and Results

3.1. Descriptive statistics

Table 1 presents the averages and standard deviations of the four blocks of measures of individual driving performance, emotional dimensions, visual parameters and road space occupied by a platoon of 8 DD followers.

	DD		DI	
Parameter	M	SD	M	SD
Skin conductance in μS	13.98	5.21	11.94	4.81
Valence (1=displeasure; 9= pleasure)	6.00	1.53	5.80	1.65
Arousal (1= aroused; 9= relaxed)	3.57	1.76	5.23	1.72
Dominance (1= dominated; 9= dominant)	5.53	1.85	6.90	1.73
Frequency of eye fixations	142.68	9.48	134.63	11.39
Average duration of eye fixations in ms	370.23	28.32	555.19	91.40
Dwell time in ms	57205	2885	61929	2441
Frequency of revisits	24.57	3.09	39.27	4.47
Number of accelerations	176.93	92.66	78.27	73.16
Number of decelerations	119.83	34.08	51.27	39.97
Number of collisions	1.87	2.03	0.17	0.46
Distance to lead vehicle in m (M)	5.86	1.01	11.56	4.30
Distance to lead vehicle in m (SD)	3.72	0.68	4.25	0.94
Speed in m/s (M)	3.08	0.03	3.07	0.03
Speed in m/s (SD)	2.60	0.28	1.40	0.71
Distance from lead vehicle to 8th vehicle in m (M)	107.06	1.31	102.78	5.56

Distance from participant vehicle to 8th vehicle in m (M)	101.20	1.28	91.22	6.63
Virtual fuel consumption (liters)	17.92	1.26	14.50	1.88

Table 1. Descriptive statistics for DD and DI

3.2. Inferential analysis

The four blocks (driver's performance, emotional dimensions, visual behavior and road space occupied by DD followers) were subjected to repeated-measures ANOVA having two levels of driving orientation (DD, DI) as within-subject factor and controlling the order (DD-DI, DI-DD) as between-subject factor. To simplify the exposition, emotional dimensions and visual patterns will be described first, and individual driving performance and collective occupancy of road space will be summarized together.

SC measures of arousal were analyzed in a 2 (DD, DI) x 2 (DD-DI, DI-DD) ANOVA. The analyses yielded significant differences for SC under DD vs DI, $F_{(1,28)} = 30.68$; $p = .0001$, $\eta_p^2 = .523$ (table 1). Fig. 4 shows the pattern of skin conductance variations through the task under DD vs DI for the whole group. Although skin conductance was roughly equal at the beginning of the task both lines separated and differences become more acute as the task progressed. DD drivers kept a higher level of arousal throughout the task than did DI drivers.

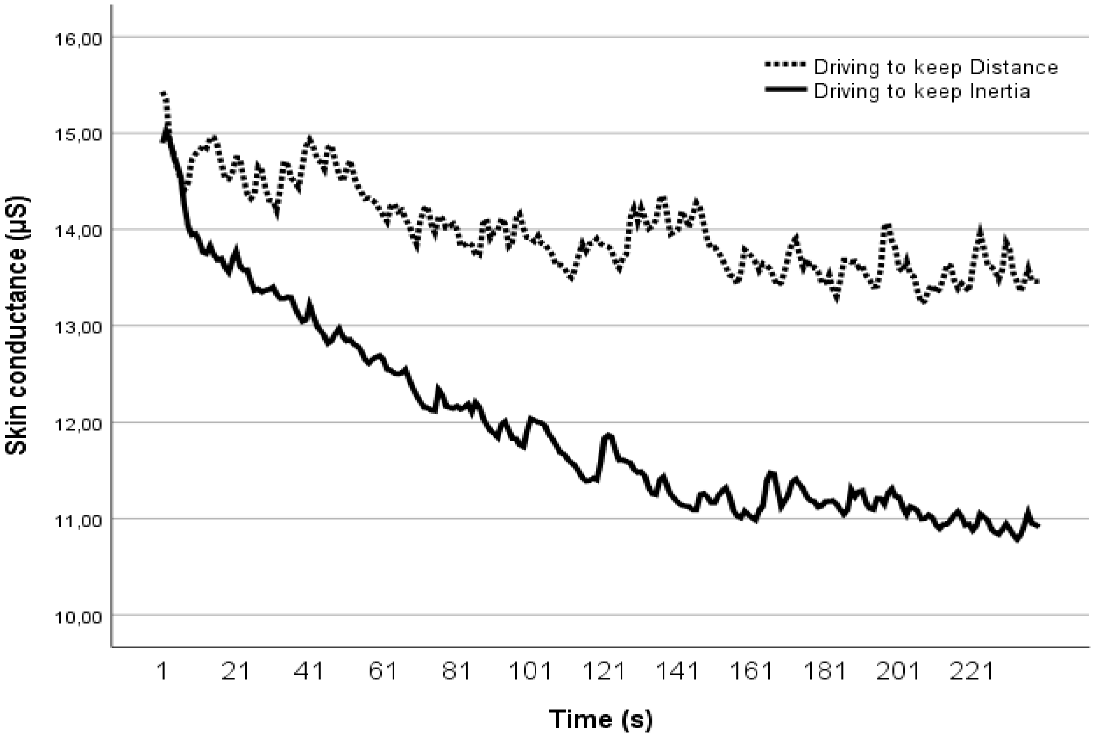

Figure 4. Drivers' arousal while performing the car-following task.

Self-reports on emotional dimensions were analyzed in a 2 (DD, DI) x 3 (valence, arousal, dominance) x 2 (DD-DI; DI-DD order) ANOVA. The aggregate measure of the three SAM dimensions differed for each driving technique, $F_{(1,28)} = 13.91$; $p = .001$, $\eta_p^2 = .332$. DI (*M*= 5.98) was higher than DD (*M*= 5.03). SAM subscales also differed, $F_{(2,56)} = 19.62$; $p = .0001$, $\eta_p^2 = .412$. The arousal scores (*M*= 4.40) were lower than the valence (*M*= 5.90, $p = .001$) and dominance scores (*M*= 6.22, p = .001), but valence and dominance did not differ each other ($p = .36$). Both factors yielded an interaction, $F_{(2,56)} = 17.31$; $p = .0001$, $\eta_p^2 = .382$ (table 1). Differences between DD and DI in terms of valence were not significant ($p = 0.54$) but arousal ($p = .001$) and dominance ($p = .001$) differed.

The four variables concerning visual behavior (frequency and average duration of eye fixations, dwell time and revisits) were analyzed in a 2 (DD, DI) x 3 (TRC, BRC, WSA) x 2 (DD-DI; DI-DD) ANOVA. Results showed no differences between DD and DI in the frequency of eye fixations ($p = .48$; table 1). Mauchly’s W test indicated that the assumption of sphericity was not reached, neither for the eye movements regions ($X^2_{(2)} = 6.45$, $p = .04$, Chi-square) nor for the within-subject factors interaction ($X^2_{(2)} = 20.26$, $p = .001$). Therefore, degrees of freedom were corrected using Greenhouse-Geisser estimates of sphericity ($\varepsilon = .83$ and $\varepsilon = .65$, respectively). The frequency of eye fixations differed for each region, $F_{(2,56)} = 94.85$; $p = .0001$, $\eta_p^2 = .772$. The TRC region received less fixations (*M* = 25.38), than BRC (*M* = 296.51) and WSA eye fixations (*M* = 94.07; all mean differences significant at $p = .001$). An interaction was found, $F_{(2,56)} = 13.46$, $p = .0001$, $\eta_p^2 = .325$. The TRC eye fixations did not differ in terms of driving technique (DD: *M* = 31.70; DI: *M* = 19.07; $p = .23$), but the BRC (DD: *M* = 352.17; DI: *M* = 249.87; $p = .002$) and WSA ones did (DD: *M* = 56.80; DI: *M* = 131.13; $p = .002$). While DD drivers focused comparatively more on the BRC (i.e., keeping a visual scanning based on smaller vision angles), DI ones focused more on WSA, the surrounding area (keeping wider vision angles).

The mean duration of fixations differed for DD and DI, $F_{(1,28)} = 4.79$; $p = .037$, $\eta_p^2 = .146$ (table 1), and for each region too, $F_{(2,56)} = 7.74$; $p = .001$, $\eta_p^2 = .217$. The TRC region received shorter mean fixations (*M* = 346.62 ms), than the BRC (*M* = 544.98 ms) and WSA regions (*M* = 496.54 ms). Differences TRC-BRC (p = .002) and TRC-WSA were significant ($p = .011$); differences BRC-WSA were not ($p = .29$). No interactions were found.

Dwell times, the time spent in the same area, differed in terms of driving technique, $F_{(1,28)} = 12.98$; $p = .001$, $\eta_p^2 = .317$ (table 1). Mauchly’s W test indicated that the assumption of sphericity was not reached, neither for the region factor ($X^2_{(2)} = 10.90$, $p = .004$) nor for the interaction between within-subject factors ($X^2_{(2)} = 44.08$, $p = .0001$). Corrected Greenhouse-Geisser estimates of sphericity were adopted ($\varepsilon = .75$ and $\varepsilon = .55$, respectively). Dwell times differed for each region, $F_{(2,56)} = 97.45$; $p = .0001$, $\eta_p^2 = .777$, being shorter on TRC (*M* = 8490 ms), than on BRC ($M = 128692$ ms) or WSA regions ($M = 41519$ ms; all mean differences were significant at $p = .0001$). Both factors yielded an interaction, $F_{(2,56)} = 12.18$, $p = .001$, $\eta_p^2 = .303$: the TRC dwell times were shorter for DD ($M = 5381$) than for DI ($M = 11598$; $p = .035$); BRC dwell times were longer for DD ($M = 145590$) than for DI ($M = 111795$; $p = .005$), and WSA dwell times were again shorter for DD ($M = 20644$) than for DI ($M = 62394$; $p = .0001$). Overall, DD drivers focused longer on BRC (Fig. 5, A), while DI ones focused longer to TRC and WSA regions (Fig. 5, B).

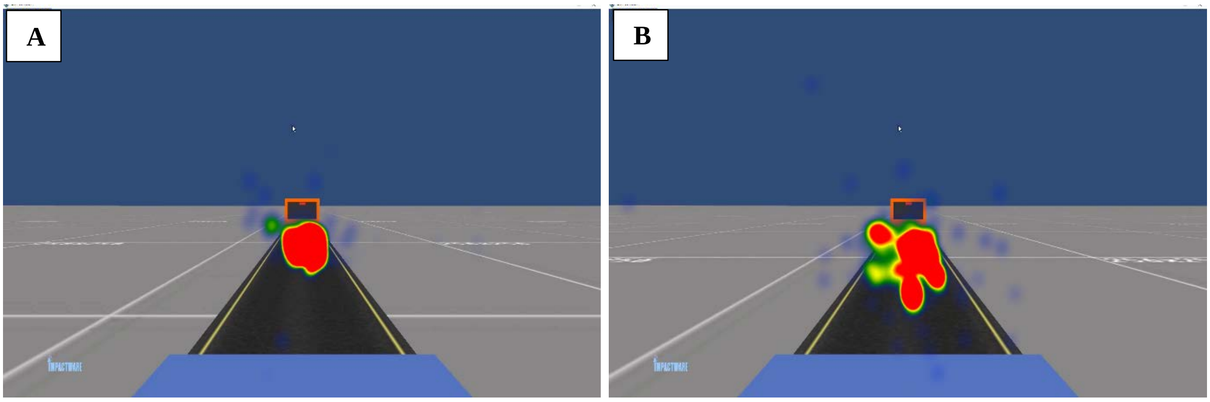

Figure 5: Two examples of heat points under DD (A) and DI (B).

Revisits, an index of visual activity that indicates when the fixation changes from one of the three regions to another region which had been previously seen, differed for DD vs DI, $F_{(1,28)} = 14.23$; $p < .001$, $\eta_p^2 = .337$ (table 1). Again, the assumption of sphericity was not reached, for the region factor ($X^2_{(2)} = 45.93$, $p = .0001$) and for the interaction between within-subject factors ($X^2_{(2)} = 15.30$, $p = .0001$). Degrees of freedom were corrected using Greenhouse-Geisser estimates of sphericity ($\varepsilon = .55$ and $\varepsilon = .70$, respectively). The amount of revisits differed among regions, $F_{(2,56)} = 35.78$; $p = .0001$, $\eta_p^2 = .561$. TRC revisits were fewer ($M = 14.08$), than BRC ($M = 44.52$) and WSA revisits ($M = 37.15$; all mean differences significant at $p = .001$). Driving technique and region interacted, $F_{(2,56)} = 6.58$, $\mathrm{p} = .003$, $\eta_p^2 = .190$. The TRC region did not show differences in revisits in terms of driving technique (DD: $M = 11.13$; DI: $M = 17.03$; $p = .11$), but differences were significant for BRC (DD: $M = 35.57$; DI: $M = 53.47$; $p = .002$) and WSA regions (DD: $M = 27.00$; DI: $M = 47.30$; $p = .0001$). Finally, the driving technique, region and order interaction was significant too, $F_{(2,56)} = 4.82$, $p = .012$, $\eta_p^2 = .147$. Although no effect was hypothesized for order, we aimed to check the impact of order on the DD/DI x region interaction (e.g., if beginning with DI influences the way regions are explored under DD). Post hoc simple second-order interaction effects indicated no significant differences for DD-DI vs DI-DD considering TRC ($p = .92$) BRC ($p = .41$) or WSA ($p = .31$) regions under DD. Similarly, the analysis yielded no significant differences for DD-DI vs DI-DD considering TRC ($p = .19$) BRC ($p = .94$) or WSA ($p = .71$) regions under DI.

We now turn to the block of performance measurements. Accelerations and decelerations were analyzed in a 2 (DD, DI) x 2 (Acc., Dec.) x 2 (DD-DI, DI-DD) ANOVA. Results showed a greater number of acceleration/deceleration operations under DD (*M*= 148.38) than under DI (*M*= 64.77), $F_{(1,28)} = 31.417$; $p =$ .0001, $\eta_p^2 = .529$. Overall, accelerations (*M*= 127.60) were more frequent than decelerations (*M*= 85.55), $F_{(1,28)} =$ 20.063; $p = .0001$, $\eta_p^2 = .417$. Both factors (DD/DI; Acc./Dec.) yielded a marginal interaction, $F_{(1,28)} = 4.14$, $p =$ .051, $\eta_p^2 = .129$ (table 1): although accelerations are always more frequent than decelerations, under DD the ratio between accelerations and decelerations (67.73%, $p = .001$) was somewhat more marked than under DI (65,50%, $p = .004$).

Each of the remaining performance parameters was analyzed in a 2 (DD, DI) x 2 (DD-DI, DI-DD) ANOVA. Speed and distance represent the fundamentals of DD and DI driving techniques. DD/DI differences on average speed were only marginal, $F_{(1,28)} = 3.47$; $p = .072$, $\eta_p^2 = .111$, but the average speed dispersion differed significantly, $F_{(1,28)} = 153.142$; $p = .0001$, $\eta_p^2 = .845$ (Table 1), being higher under DD. Fig. 6 shows speed under DD and DI along 4 minutes for the whole sample (note the brief initial adaptation phase, then a stabilization, and the wider speed range for DD).

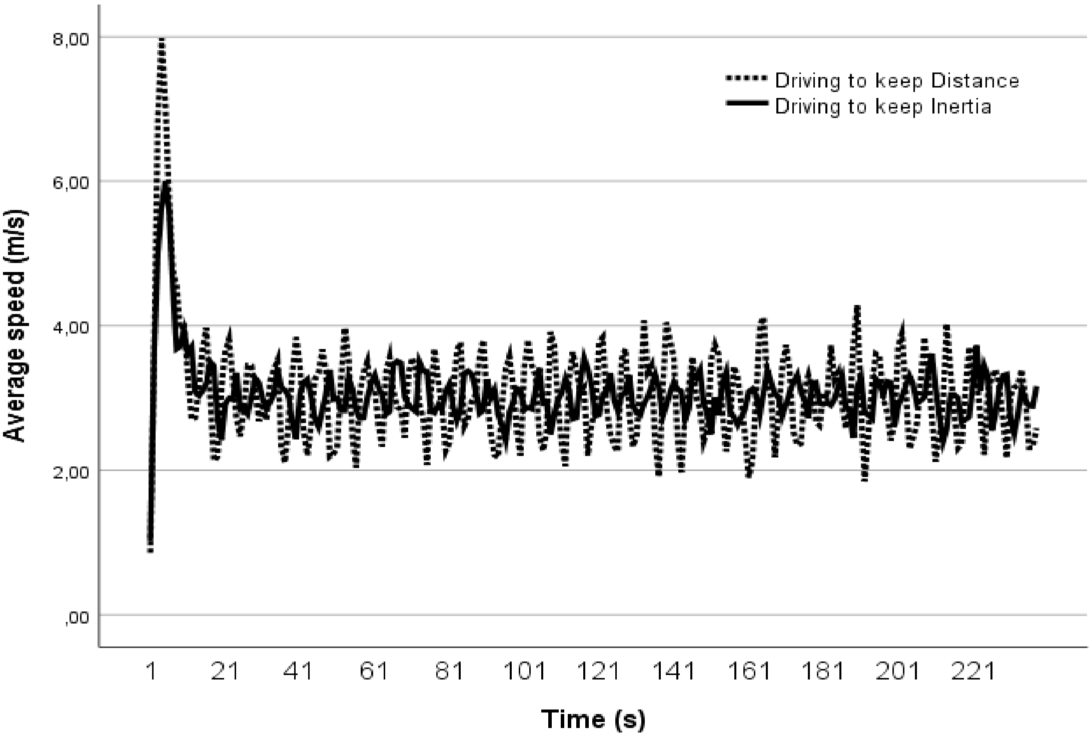

Figure 6: Average speed throughout the task for DD versus DI.

Conversely, results indicated that the average distance to the leader was shorter under DD than DI, $F_{(1,28)} = 52.83$; $p = .0001$, $\eta_p^2 = .654$ (table 1). The mean variations of distance while following the leader yielded smaller dispersions under DD than under DI, $F_{(1,28)} = 8.210$; $p = .008$, $\eta_p^2 = .227$. Fig. 7 shows the distance to leader kept when DD vs DI techniques were applied.

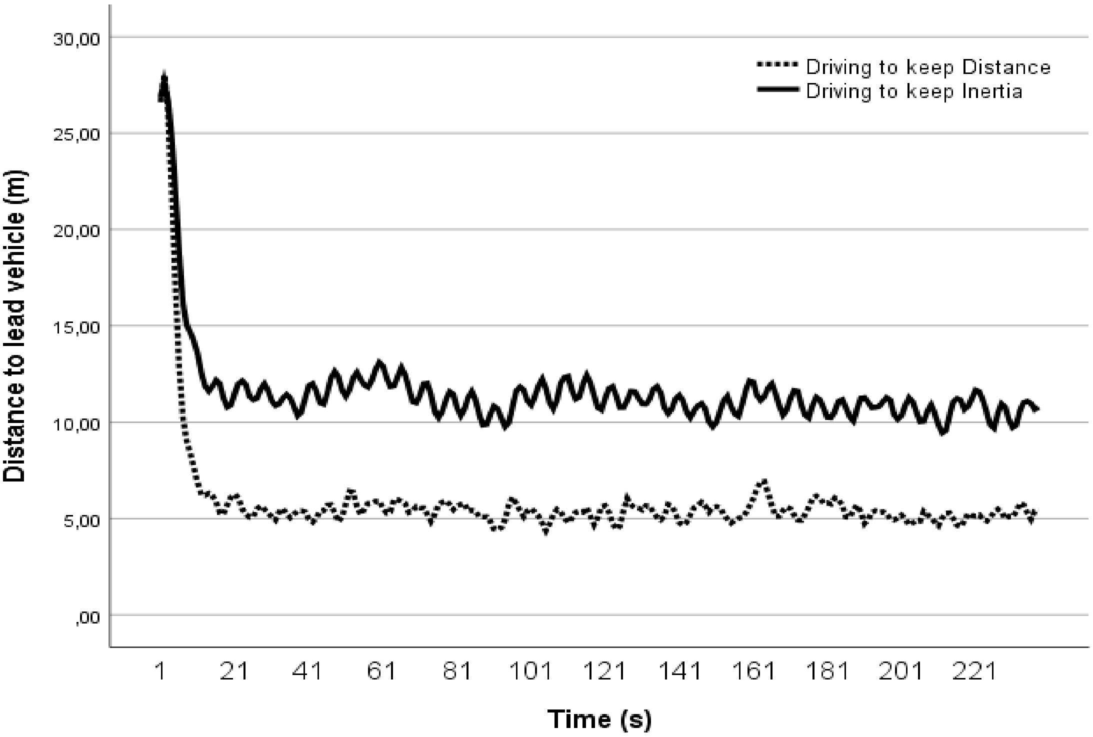

Figure 7: Average distance to the leader throughout the task for DD versus DI.

With regards to collisions, significant differences were found for DD vs DI, $F_{(1,28)} = 21.62$; $p = .0001$, $\eta_p^2 = .436$ (table 1). Overall, DD drivers accelerate and decelerate more, adopting a similar average speed but higher speed dispersion, and smaller distance to the leader, with lower distance variations, i.e., they assume a CF context with more disturbances and a higher crash probability. Real-life points to congestion as the main context for rear-end collisions too (Davis and Swenson, 2006; SWOV, 2010). Finally, in agreement with the previous data (accelerations, decelerations, speed and distance variability), the average fuel consumption was about 20% greater for DD compared to DI, $F_{(1,28)} = 236.411$; $p = .0001$, $\eta_p^2 = .894$.

The road space occupied by the 8 DD-virtual car platoon was then considered (the simulator systematically stored the X coordinate of the reference vehicles -leader, participant and last vehicle of the following platoon- each second along the whole trip). The distance between the participant's vehicle and the 8th vehicle was longer under DD than under DI, $F_{(1,28)} = 74.99$; $p = .0001$, $\eta_p^2 = .728$. And also the distance between the lead vehicle and the 8th vehicle was longer for DD than for DI, $F_{(1,28)} = 18.31$; $p = .0001$, $\eta_p^2 = .395$ (table 1). Both results are of interest, considering Figs. 6 and 7: although the distance between the participant and the leader is greater under DI (the so-called anti-jam distance must be kept), the 8 DD-followers occupied less road space. So the wave-offsetting distance DI participants needed to keep inertia, stabilized the coming traffic behind, fostering a stable, shorter platoon of DD followers and less road occupancy overall.

Focusing on DD/DI as indicated by the η_p^2 scores, the effect size for the cognitive-affective factors was medium-sized (.523 for the DD/DI differences in skin conductance, .382 for the interaction DD/DI x SAM subscales). With regards to the eye-movements, effects were small to middle-sized, and we would underline the DD/DI x Region interaction for eye fixations (.325), and for dwell time (.303). The effect size associated with performance factors was wide-ranging, some of them were large. DD/DI differed for accelerations/decelerations (.529), the amount of collisions (.436), the average distance to the lead vehicle (.654), but most importantly for the speed variation (.845), the distance between the participant’s vehicle and the last one (.728) and fuel consumption (.894).

4. Discussion

Summing up the results indicate that DI drivers were more efficient, felt less aroused but more dominant, displayed richer visual patterns, and were more uniformly followed by a platoon of DD virtual drivers. The evidence confirmed the psychological and behavioral validity of the WD approach to CF: the same driver could drive in DD and DI modes when following a lead ‘swinging’ car; drivers could implement the driving techniques by simply heeding a 10 s instruction (three sentences); and DI drivers kept the driving instruction as requested (i.e., not returning to DD after a while). The very same driving situation, following a leading vehicle that progress amidst a series of stop-and-go cycles, can be confronted by adopting two essentially different CF techniques. This statement completely changes our perspective of how it is possible to organize traffic flows; so far we have only taken half of the possibilities.

The block of performance measures accurately characterizes these two opposing approaches to vehicular flow. In line with what Sugiyama et al. (2008; Tadaki et al., 2013) observed in Nagoya, DD is only possible at the expense of strong speed variations, which in turn demands more frequent accelerations and decelerations (Fig. 6). This performance pattern produced results concerning individuals’ health. On the one hand, a road safety problem derived from a greater probability of rear-end collisions (Davis and Swenson, 2006; SWOV, 2010). On the other hand, a public health issue derived from a higher fuel consumption leading to polluting emissions (Caiazzo et al., 2013). In turn, DI is only possible if reconsidering and anticipating the right CF distance through a proper decomposition of safety and anti-jam distances (Fig. 1, B; Fig. 7). However, rethinking CF in this way has its logical reward: fewer accelerations and decelerations, fewer accidents and fuel consumption, with the consequent gain in health. Note that the very same swinging leader, keeping the same average speed, was followed driving DD/DI at virtually equal average driving speeds. Results concerning the block of performance measures of the present study consolidate findings in previous studies (Blanch et al., 2018; Carrasco, 2017; Taniguchi et al., 2015).

The block of affective dimensions includes psychophysiological (skin conductance) and self-report measures (SAM scales), and also points to individual health issues. Overall, DD occurred at the expense of greater arousal and less sense of dominance whereas DI required less arousal yet prompting feelings of dominance. Skin conductance, controlled by the sympathetic branch of the autonomous nervous system, shows DD/DI curves move away from each other over time (Fig. 4) yielding neat DD/DI differences. It is important to note the coincidence of psychophysiological (skin conductance) and self-report (SAM scale) measures of arousal (Lang, 1980; Lang et al., 1999): both differ significantly for DD and DI. These results, including self-reports of enhanced dominance under DI, replicate previous findings (Lucas-Alba et al., 2017). Arousal is a fundamental emotional dimension, along with valence. Aroused drivers can be happy or angry, depending on valence. If the driver goals are blocked by third parties (quite common in congestion), drivers frustrate and become angry (Mesken et al., 2007; Zhang and Chan, 2014) giving way to behaviors as tailgating or lane change (Shinar and Compton, 2004; Deffenbacher et al., 2003; Abdu, Sinar and Meiran, 2012), what in turn worsens congestions. However, our study does not present DI/DD differences in valence, the CF task was generally experienced as moderately and equivalently pleasant (Table 1). Manipulating valence and eliciting discrete emotions remains as a due challenge for future studies. Analyzing DD/DI in terms of fundamental psychological needs (autonomy, competence, and affinity; Reeve, 2018) could also be relevant. If perceived as an undue constriction of freedom, a loss of autonomy may give way to psychological reactance, a motivational state with compelling behavioral properties (Steindl et al., 2015). Helping drivers understand and manage CF under a DI perspective should enhance feelings of autonomy and competence, a true traffic calming measure.

The block concerning visual behavior under the DD/DI techniques was an entirely new exploration. Visual parameters (fixations, dwell times, revisits) differed for DD and DI in terms of the region under scrutiny (top rear car, bottom rear car, and white space area –i.e. the wider area surrounding the car). While Driving to keep Distance drivers' perceptual focus narrowed into the BRC region: more fixations, and longer dwell times, but less revisits. This visual pattern corresponds to a rather small visual angle span and visual immobility: drivers kept concentrated around the braking light's area. DD drivers' visual behavior to keep safety distance relied substantially on BRC and drivers are normally good at estimating time to crash based on upon stereoscopic depth perception and visual angles subtended by a lead vehicle (Gray and Regan, 1998). In the Action Point paradigm, visual angle models define the follower action in terms of the perceived horizontal visual angle between the followers' retina and the width of the leader's vehicle (Pariota and Bifulco, 2015; Saifuzzaman and Zheng, 2014). This concept is adopted to examine the driver's ability to scale the relative velocity between the vehicles (Yousif and Al-Obaedi, 2011). According to visual-angle CF models, DD drivers would be expected to accelerate/decelerate as a function of angular velocity (e.g., when the just noticeable difference threshold exceeds 10%) (Brackstone and McDonald, 1999), and so they would pay attention to the BRC area width in particular (braking lights). Besides this basic perceptual mechanism, our inquiry concerns the visual strategy adopted looking ahead while following the very same type of swinging leader, grossly labeled as the expert (anticipatory) vs novel (reactive) approaches. The results indicate that while Driving to keep Inertia the focus extended to the WSA region: more fixations, and longer dwell times, but also more revisits were obtained coupled with more revisits into the BRC region too. This visual pattern corresponds to larger visual span and visual dynamism: the DI driver looked ahead (WSA) but alternated more between different zones, so revisits changed from BRC to WSA, back and forth. It is interesting to note how DD kept wide speed variations at the expense of rigid visual scan while driving DI aims for a uniform speed based on a rather flexible and dynamic visual behavior (Fig. 5). Keeping a uniform speed requires decomposing CF distance into safety and anti-jam zones. Hence, DI drivers also needed to pay attention to BRC while taking safety distance into account (as DD drivers did). However, this work was complemented with anticipations concerning the anti-jam zone (damping the leader oscillation and keeping a uniform speed). This calculus was probably not only based on immediate visual cues but some type of visual heuristic or scheme built on the fly (DeLucia, 2013). Future work should answer to this basic question: how difficult is learning and adopting the perceptual schemes and anticipations that bring on a successful DI technique under different CF circumstances (e.g., varying stop-and-go patterns of the lead vehicle, traffic density, relative size of the preceding vehicle, and the like; DeLucia, 2013).

The fourth block focuses on variations observed on the platoon of DD followers and brings the Nagoya paradigm (Sugiyama et al., 2008) one step beyond (see Stern et al., 2018 for results with autonomous vehicles). Each of the eight DD vehicles following participants reacted equally to changes in speed and distance of the preceding vehicle. Driving to keep Inertia requires additional anti-jam space to offset disturbances emitted by the leader (Fig. 7). However, the DD followers required more road space than DI followers, not only when the distance between the participant and the 8th follower is considered, but also considering the stretch between the leader and the very last vehicle. So the wave-offsetting anti-jam distance required to keep inertia was key to stabilize traffic behind, reducing the road space needed and forming a compact, uniform platoon. However, the WD approach warns about the way the 4th variable, the unused or remaining space, is managed. Learning to do it properly is important. In a previous study (Blanch et al., 2018; study 3) participants were not trained to evaluate perceptual cues following the leader; as a result, differences in road space between leader and 8th vehicle were similar for DD/DI (although differences in road space between participant and 8th vehicle differed significantly). Participants in the present study were invited to explore that cues properly in a previous task (at Scenario B, participants were requested to coming close and familiarize with vehicle dimensions while following a leader at constant speed). The result is that both the absolute and relative space required by the 8th DD following platoon diminished under DI. This result turns into a basic principle of traffic wave dynamics: to achieve platooning at uniform speeds, the speed fluctuations and distance to the preceding vehicles must be properly understood and managed. There is a growing consensus that automation will be surely accompanied by a reduction in time headway, and some researchers expect negative effects after the interaction between automated vehicles and unequipped vehicles begins (Gouy et al, 2014). However, studies focusing on Adaptive Cruise Control have shown that platoon stability emerges with a sufficient gap: only with a short gap, the instability predominates (Ploeg, Wouw, and van de Nijmeijer, 2014). Perhaps reducing time headway is not a good idea after all –dense platoons are the places where disturbances flow better, also between robots, connected or automated cars, that's a law of nature. This is also why autonomous vehicles that are successfully keeping a stable flow by calculating the average speed of the platoon (Stern et al., 2018) may be in trouble if speed fluctuations of some vehicles ahead are not rightly anticipated and timely compensated adjusting the anti-jam distance.

4.1. Limitations

The main objective of this research was to characterize two driving techniques (DD / DI) considering both the variables of the individual driver (including behavioral, emotional and perceptual factors) and a group of eight following drivers (the road space occupied by the platoon). Results are robust and relevant but some aspects may be improved. The sample was made of young, relatively inexperienced drivers, most of them university students, and a wider sample with older and more experienced drivers should be also tested. The driving simulator was a simple one, and served our purposes functionally, but a more sophisticated simulator (with gas/brakes pedals and a wheel, wider screen, movement, a more realistic scenario, and a more specific energy consumption model) would be a convenient step to follow (also the use of Instrumented Vehicles). However, besides simulation quality and sophistication, essential factors need not be overlooked. Consider this video comparing the experiment in Nagoya (Sugiyama et al., 2008) with a few robot drivers (https://bit.ly/3gIELi6). Both human drivers and robots adopt the same car-following algorithm (driving with two variables) and so create the same effect: congested groupings by soliton waves. There are many differences between them, but both human drivers and robots comply with physical laws. DD and DI are techniques that require opposing driving strategies in mathematical (number of variables), physical (keeping distance vs inertia), and behavioral terms. To drive DD vs DI, drivers need resorting to strongly opposed mechanisms in attentional, perceptual, and cognitive-emotional terms. Such differences were, in this early stage of our research, made clear in our simulator. Having said this, it is sensible to introduce more realism in future studies. For example, although some pilot tests with real cars in a closed circuit have confirmed the expected outcomes regarding DD/DI (https://bit.ly/2XnQiMo), complementing the cognitive, emotional and behavioral exploration of DD and DI in a driving simulator with more standard functionalities (e.g., with accelerator/brake pedals) and greater realism (e.g. reproducing urban or interurban settings) seems an important objective. Also, the speed of the lead car in our study was very low (reproducing stop-and-go congested traffic) and examining a wider range of speeds would be also convenient, not to mention the fact that merging, overtakes and multiple lanes are perturbing elements that feed congestions as well. Indeed, real traffic jams often involve more complex situations for the driver than Nagoya's circle. Manipulating valence to elicit specific discrete emotions (e.g., anger, anxiety) would be another important goal.

Although we must continue to delve into the WaveDriving concept, it is possible to glimpse some practical applications. Phantom traffic jams (that is, traffic jams caused by interference of speed) have many different causal factors: for example, changes in speed limits (before a curve, a tunnel entrance, signaling road works), changes in the geometry of the route (curves, slopes), even distractions (near-road publicity), are some of the most common causes. The future lies in driver education, but different anticipatory strategies combining police enforcement and variable message signs could contribute greatly to appease and stabilize the flows.

5. Conclusions

WaveDriving could be a determinant and act proactively as a bottom-up element against traffic flow's oscillatory nature, a decisive contribution towards uninterrupted traffic flows. DI was more efficient than DD, either considering driving parameters, cognitive-emotional or collective ones. DD and DI are two altogether different alternatives to follow a swinging leader, but participants adopted and kept them as requested, yielding clear and consistent differences in terms of speed dispersion, CF distance and distance variability, rear-end collisions and fuel consumption. Emotional dimensions differed as well: drivers felt less aroused and more dominant driving DI than driving DD. Visual patterns also differed for DD and DI in terms of attentional focus (fixations and dwell times upon BRC vs WSA/TRC), visual span and scanning variability (revisits). Finally, in spite of the supplementary anti-jam distance required to keep inertia while following a swinging leader, the platoon of DD followers occupied less road space when DI was adopted.

Some of the experimental and working conditions of this study can indeed improve (the sample, the simulator, manipulating valence, the range of speeds of the leader) and will form part of the future directions of our work. Another important line of research (sharpened by the COVID 19 issue) concerns developing a proper WD learning environment (Melchor et al., 2018). However, the present results consolidate an elementary reinterpretation of the traffic flow, with potential repercussions on its sustainability, land-use planning and commercial and leisure mobility. Talking about road capacity may be somehow deceptive. Road functionality should rely on how flows are ordered. The same road, even the same leading behavior, yields differing order and road occupancy for the following platoon depending on the driving technique and strategy applied. Paraphrasing Norbert Wiener (1950), one may say that each single driver can be essential in bringing order to the natural entropy of dynamic systems such as traffic flows. Drivers can mentally model the present dynamics of traffic ahead and damp oscillations – not contributing to the problem, but to the solution. Some researchers anticipate difficulties mixing human and non-human drivers in the flows (Gouy et al., 2014). Why should not drivers (human and automated) keep similar CF strategies in favor of mobility? Longitudinal mechanical waves are instruments of nature that serve different types of movement, and automatons are committed too. Adopting a comprehensive stance is key reaching the functional integration of moving humans and robots alike.

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